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# Diffused-Quantum-Well Vertical Cavity Fabry-Perot Reflection Modulator

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**Abstract** - This is a first report to use diffused quantum well (DFQW) as the active cavity of the Fabry-Perot reflection modulator. Apart from the simple fabrication process of the DFQW, this material system provides a wavelength tuning range and improves the modulation properties of the device which thus is competitive to the same kind of modulator.

## I. INTRODUCTION

Currently, surface-normal Fabry-Perot (FP) etalon modulators based on III-V multiple quantum well (MQW) semiconductors for potential applications such as two-dimensional arrays for interconnection, and optical processing have gained considerable interest. This type of modulator has the advantage of providing a large area in the coupling of light in and out of the device and is compatible with vertical opto-electronic integrating technology [1]. Moreover, this structure of modulator provides long effective optical interaction path and thus reduces the applied voltage swing [2]. In this work, annealing induced non-square diffused-QW (DFQW) structure[3] is first introduced as the intrinsic material in the asymmetric-FP vertical cavity so that the operation wavelength  $\lambda_{op}$  of the modulator can be fine tuned by controlling the disordering of regular as-growth QW. This structure can serve as a high performance FP modulator by improving the modulation properties and providing an operation wavelength tuning range. It is expected that this DFQWs based FP modulator will become an important candidate for the vertical integrating technology. The electro-optical effects of DFQW structure on the total reflectance  $R_{tot}$  of the modulator are analyzed together with the figures of merit, change of  $R_{tot}$ , ( $\Delta R_{tot}$ ), and the ratio  $\Delta R_{tot}/R_{tot}$ .

## II. MODELING

We consider the DFQW resonant-etalon reflection modulator structure in a simple way, as shown in Fig. 1(a), where the inner intrinsic DFQW consists of 61 periods of 101Å/100Å  $Al_{0.3}Ga_{0.7}As/GaAs$ . The extent of diffusion is characterized by a diffusion length  $L_d$  ( $L_d = 0$

represents the as-growth QW) [3]. The front and back quarter wavelength Bragg reflectors are alternative AlAs and AlGaAs layers with reflective indices taken from [4] which are p- and n- doped as in a p-i-n structure. The bottom reflectance  $R_b$  is set at about 0.97, the top one  $R_t$  is calculated from the relation  $R_t = R_b \exp(-2\alpha_c l_c)$  where  $l_c$  and  $\alpha_c$  are the cavity length and absorption coefficient respectively,  $\alpha_c$  is calculated from a model similar to [5] without the polarization sensitivity; the relation of  $R_t$  is the impedance-matching condition for zero total reflectivity at resonance[2] so that the contrast ratio CR of the modulation can become infinity. The reflectance of the FP modulator can be calculated by using the scattering matrices method as shown in Fig. 1b. The arrow indicates the direction of propagation of the field, where F (forward) and B (backward) are the electric field of the light. The total reflectance is defined as  $R_{tot} = (B_1/F_1)^2 = |(s_{21} + R_{B5} s_{22}) / (s_{11} - R_{1T} s_{12})|^2$ , where  $R_{B5}$  and  $R_{1T}$  are the reflectance of the interface between (B, 5) and between (1, T) respectively, the negative sign of  $R_{1T}$  indicates that the refractive index of medium T is higher than that of medium 1 since medium 1 is considered to be air ( $n_{air}=1$ ), and  $s_{ij}$  are the matrix elements of a  $2 \times 2$  scattering matrix S. S is defined as  $M_T \times M_{QW} \times M_B$ , where  $M_j$  is the scattering matrix of region j for  $F_j = m_{j11}F_{j+1} + m_{j12}B_{j+1}$  and  $B_j = m_{j21}F_{j+1} + m_{j22}B_{j+1}$ ,  $m_{jab}$  are elements of  $M_j$ , and the subscripts a and b are integer 1 or 2. It is assumed that the field in top and bottom reflectors (medium T and B) will only undergo phase change without any residence loss while the field in the intrinsic DFQW layer will involve both phase changes  $\exp(i\delta_c l_c)$  and loss  $\exp(-\alpha_c l_c)$ . The phase change per unit length is defined as  $\delta_i = 2\pi n_i / \lambda_{op}$  where  $n_i$  and  $\lambda_{op}$  are the refractive index of medium (i) and the operational wavelength, respectively.

## III. RESULTS

It is interesting to note that the FP modulator can operate at FP mode for cases from  $L_d$  0 to 40 Å stepped by 10Å without any re-design of the active region of the modulator. However, since the operation wavelength will shift while the QW structure undergoes an interdiffusion,

the top and bottom Bragg reflectors, the number of the alternative layers, and the thickness of each quarter wavelength layer have to be rearranged. The number of period of top and bottom reflectors are 8.5 and 16.5 of alternative 734Å (AlAs) and 639Å ( $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ) respectively when the cavity structure is as-growth square wells ( $L_d=0$ ). While the QW structure undergoes an interdiffusion to  $L_d=40\text{\AA}$ , the top and bottom reflectors will be amended to 7.5 and 16.5 periods of alternative 633 Å (AlAs) and 548Å ( $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ) respectively. As a whole, the total thickness of the modulator will be reduced for different DFQW's cavities. Table 1 shows the modulation properties of the DFQWs modulators with an identical thickness of cavity. For the cases from  $L_d=0$  to 20Å, the change of reflectance ( $\Delta R_{\text{tot}}$ ) have roughly same value. Moreover, there are two possible  $\lambda_{\text{op}}$  that the first  $\lambda_{\text{op}}$  of  $L_d=10$  will have relative low residence loss but high minimum value of  $R_{\text{tot}}$ ,  $R_{\text{tot}}(\text{min})$ , at FP mode while the second  $\lambda_{\text{op}}$  is just vice versa. The  $R_{\text{tot}}(\text{min})$  for the case  $L_d=30\text{\AA}$  is the lowest ( $1.0418 \times 10^{-5}$ ) with low residence loss. Although the  $\Delta R_{\text{tot}}$  is also reduced to minimum (0.100) when comparing with other  $L_d$ 's cases, the figure of the merit  $\Delta R_{\text{tot}}/R_{\text{tot}}$  is extremely high about 9600. If the interdiffusion is further increased to  $L_d=40\text{\AA}$ , the  $\lambda_{\text{op}}$  will further blue-shift [6] to 0.7645μm. Also the applied electric field  $F$  (kV/cm) will reduce to 50 - 80 kV/cm though the  $R_{\text{tot}}(\text{min})$  become high. All in all, the same as-growth QW cavity structure can operate between 0.8747 and 0.794μm under different interdiffusion from  $L_d=0$  to 30Å. If high  $R_{\text{tot}}(\text{min})$  is not an obstacle in an operation, the wavelength tuning range will increase to (0.8747 to 0.7645μm) about 110nm.

In fact, the whole modulation will further improve by adjusting the cavity thickness  $l_c$  for  $n\pi$  phase variation of the field in different  $L_d$ 's cases. In order to compare with the result of as-growth square QW modulator, the adjusted  $l_c$  of different  $L_d$ 's cases is set nearest to the  $l_c$  of the square QW modulator. Fig.2a and Fig.2b show the reflectance spectra of different applied field of the cases  $L_d=0$  (square QW) and  $L_d=40\text{\AA}$  respectively. For the case  $L_d=0$ , the OFF-state operated at  $\lambda_{\text{op}}=0.875\mu\text{m}$  with field  $F=130\text{kV/cm}$  while the On-state is with field  $F=0$ . It is found that the  $\lambda_{\text{op}}$  of FP mode of higher field operation will shift to shorter wavelength because the change of reflective index  $\Delta n$  of the DFQW cavity under reverse bias. The  $\Delta n$  is due to the Quantum Confined Stark Effect and can be calculated from the spectrum of the change of absorption coefficient by Kramer-Krönig relation. Moreover, for the spectra of the case  $F=0, 50$  and  $90$  kV/cm, the reflectance are close together at the  $\lambda_{\text{op}}$ . This can be explained by the packing of absorption spectra at the  $\lambda_{\text{op}}$  as shown in [7]. The  $R_r$  is designed for zero  $R_{\text{tot}}$  at  $F=130\text{kV/cm}$  (OFF-state), so from figure 2, the modulation is operated at the ON-OFF state with  $\Delta R_{\text{tot}}/R_{\text{tot}}=0.6427/3.313 \times 10^{-3}=194$ . In Fig.2b, the case of  $L_d=40\text{\AA}$ , the  $\lambda_{\text{op}}$  is blue shift to 0.7727μm. The FP resonance

with zero reflectance is operated at  $F=80\text{kV/cm}$ , the  $\Delta R_{\text{tot}}$  of ON( $F=0$ ) and OFF( $F=80\text{kV/cm}$ ) states is 0.6872 with extremely low  $R_{\text{tot}}(\text{min})$  value  $4.7633 \times 10^{-5}$ . Thus the  $\Delta R_{\text{tot}}/R_{\text{tot}}$  is as high as 15000. This value is the highest from what we recognize in the published. Moreover, the applied field required for operation also reduces from 130kV/cm at  $L_d=0$  to 80kV/cm in this case. This can therefore minimize the voltage swing. The results of other applied field are shown in Table 2. The  $\Delta R_{\text{tot}}$  increases from  $L_d=0$  to  $L_d=20\text{\AA}$  and then reduce to 0.4873 at  $L_d=40\text{\AA}$ . While the  $R_{\text{tot}}(\text{min})$  keeps very low and only within an acceptable fluctuation, the residence loss of different  $L_d$ 's cases is just between 550 and 860  $\text{cm}^{-1}$  except the second possible  $\lambda_{\text{op}}$  which can operate at low  $R_{\text{tot}}(\text{min})$ , of  $L_d=10\text{\AA}$  with residence loss  $1200\text{cm}^{-1}$ . Two outstanding cases  $L_d=30$  and  $40\text{\AA}$  are mentioned that for the case  $L_d=30\text{\AA}$ , the residence loss reduces to lowest as well as low  $R_{\text{tot}}(\text{min})$ , 350  $\text{cm}^{-1}$  and  $2.327 \times 10^{-4}$  respectively. While for the case  $L_d=40\text{\AA}$ , the applied field can be reduced to 80 kV/cm (lower power consumption) with extremely high  $\Delta R_{\text{tot}}/R_{\text{tot}}$  15000 as mentioned above. Together with the distinct feature of blue shift of  $\lambda_{\text{op}}$  and simple thermal annealing processes for producing DFQW, this FP reflection modulator will become competitive in same kind of modulator.

#### IV. CONCLUSION

In conclusion, we have analyzed the reflectivity property of a vertical cavity FP reflection modulator with different  $L_d$ 's and its electro-optical effect. The blue shift of  $\lambda_{\text{op}}$  is due to the effect of DFQW which suggests a wide band-width FP reflection modulator with  $\Delta\lambda_{\text{op}} \approx 110\text{nm}$ . Moreover, the  $L_d=30\text{\AA}$  DFQW modulator with adjusted  $l_c$  can operate at lowest residence loss and low  $R_{\text{tot}}(\text{min})$  implies highest figure of merit  $\Delta R_{\text{tot}}/R_{\text{tot}}$  while the case  $L_d=40\text{\AA}$ , only 80/130  $\times 100\%=61\%$  applied field is required and achieved highest  $\Delta R_{\text{tot}}/R_{\text{tot}}=15000$ . All these properties make the DFQWs vertical cavity modulator become competitive device.

#### ACKNOWLEDGMENT

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$L_d(\text{\AA})$	$\lambda_{op}(\mu\text{m})$	$\Delta R_{tot}$	$R_{tot}(\text{min})$	F(kV/cm) [ON-STATE]	F(kV/cm) [OFF-STATE]	$\alpha_{loss}(\text{cm}^{-1})$
0	0.8747	0.6427	$3.3125 \times 10^{-3}$	0	130	550
10	0.8564	0.6615	0.1628	0	130	860
10	0.8522	0.6482	0.0892	0	130	1200
20	0.8202	0.6899	0.00346	130	90	1090
30	0.7940	0.1000	$1.0418 \times 10^{-5}$	110	90	640
40	0.7645	0.3150	0.585	80	50	1050

Table 1. Features of the DFQW reflection modulators with an identical thickness of cavity.

$L_d(\text{\AA})$	$\lambda_{op}(\mu\text{m})$	$\Delta R_{tot}$	$R_{tot}(\text{min})$	F(kV/cm) [ON-STATE]	F(kV/cm) [OFF-STATE]	$l_c(\mu\text{m})$	$\alpha_{loss}(\text{cm}^{-1})$
0	0.8747	0.6427	$3.313 \times 10^{-3}$	0	130	1.2273	550
10	0.8564	0.7059	$3.789 \times 10^{-2}$	0	130	1.2063	860
10	0.8523	0.6300	$6.694 \times 10^{-3}$	0	110	1.2063	1200
20	0.8270	0.6612	$2.050 \times 10^{-3}$	0	130	1.2817	738
30	0.7991	0.5766	$2.327 \times 10^{-4}$	0	110	1.2399	350
40	0.7713	0.6872	$4.763 \times 10^{-5}$	0	80	1.2844	691

Table 2. Features of the DFQW reflection modulators with  $l_c$  nearest to that of the square QW modulator.

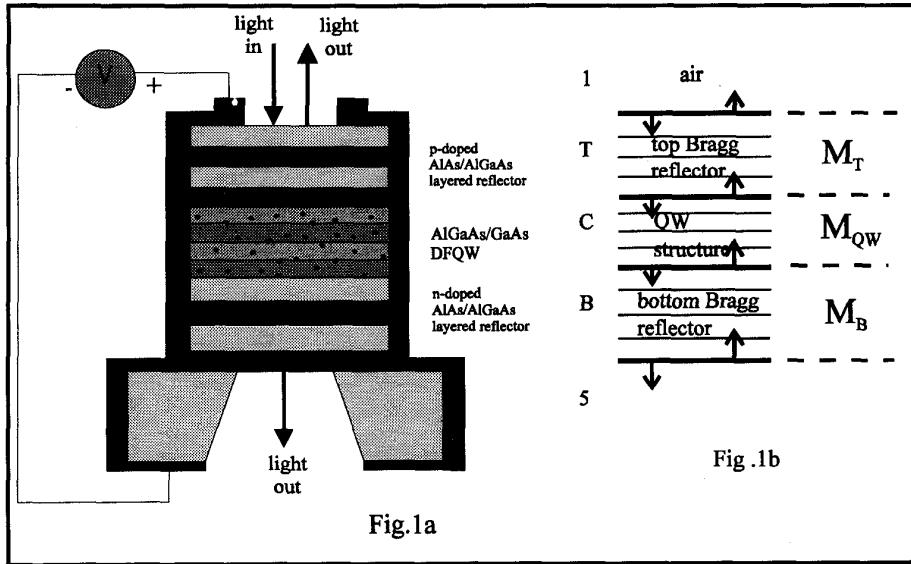


Fig. 1a Schematic cross-section of the three-section epitaxial Fabry-Perot reflection modulator  
Fig. 1b Illustration of the scattering matrices in deriving design equations.

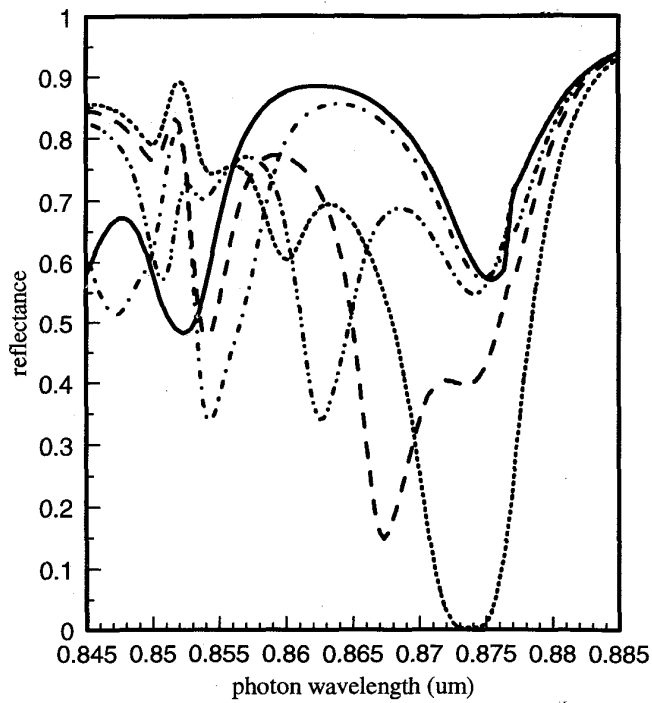


Fig.2a The reflectance spectra of  $L_d=0$  with field  $F=0$  (solid), 50 (dash-dot), 90 (dash-double dot), 110 (long-dash) and 130 kV/cm (dot).

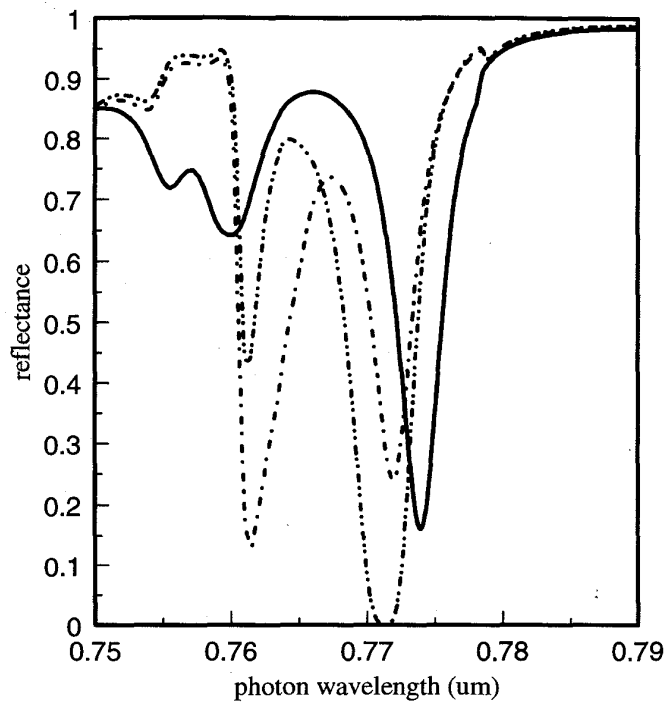


Fig.2b The reflectance spectra of  $L_d=40$  A with field  $F=0$  (solid), 50 (dash-dot), 80 (dash-double dot).